

## Space Geodesy, Potential Fields (gravity and geomagnetic) and Geomathematics

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*This new research sub-line, part of the Research Line/Department at Institute of Geosciences "Earth Dynamics and Earth Observation", includes the activities of four previously existing research groups: (i) Space Geodesy, Gravimetry and Geomathematics, (ii) Palaeomagnetism, Rock Magnetism and Geomagnetic Modelling, (iii) Terrestrial and Planetary Magnetic Field and Aeronomy, and (iv) Gravimetry, Tides and Geodynamics. These four research groups, which are included on it to work together and cooperate during the next years, have been working until now independently and with very few cooperation between them. In short, it includes the study and modelling of the Earth's (and others celestial bodies') shape, gravity and magnetic fields, and their variations in time and space, using terrestrial and space integrated geodetic, gravimetric, geomagnetic and paleomagnetic data and advanced mathematical models and techniques.*

### Scientific objectives

The scientific objectives of the research sub-line, in a non exhaustive way, can be grouped and summarized as follows:

#### Treatment of data and modelling:

- 1) Development of new data analysis mathematical techniques for geodetic, gravimetric, geomagnetic and archaeomagnetic data. In particular; fuzzy logic, Bayesian Statistics, Spherical Cap Harmonic Analysis (SCHA), Genetic Algorithm,...
- 2) Development and implementation of mathematical techniques for the integration of different kinds of geodetic terrestrial and space data (InSAR+GPS, Optical+InSAR+GPS,...).
- 3) Time series analysis and system identification using geodetic and geophysical observations.
- 4) Development of a new regional model of the Eurasian geomagnetic field for the last 8000 years. The new model will apply the RSCHA technique to obtain a model that permits prolongation in  $r$ . In addition, Bayesian statistics will be introduced into SCHA and RSCHA modelling.
- 5) Development of a first regional palaeosecular variation model for North America based on archaeomagnetic data by using the RSCHA technique.

6) Improve the method of detecting ionospheric bubbles by increasing equipment sensibility and mathematical treatment. Apply the improvements to the study of the equatorial South American anomaly using Argentinian observatory data.

Development of applications:

7) Development of deformation models for volcanic loading, earthquakes and land instability by using the new and existing geodetic observations. Models will be applied and tested to data from different areas (e.g.: Canary Islands, Spain; Long Valley Caldera, USA; Campi Flegrei and Etna volcano, Italy; earthquakes, etc...).

8) Study of crustal deformation and gravity changes in active areas using classical geodetic techniques and geodynamic stations (e.g., Canary Islands).

9) Development of new techniques to study and determine crustal structure and to carry out prospection by means of geodetic and geophysical data (e.g., using gravity data and combining gravity and seismic data).

10) Refine archaeomagnetic dating through field modelling. Application to dating volcanic activity in Italy and in the Canary Islands.

11) Comparison between variations in the archaeomagnetic field during the last 8000 years and climatic variations.

13) Revision of palaeomagnetic poles for the Iberian microplate and paleomagnetic rotations in the Betic Cordillera: constraints to tectonic modelling.

Potential fields (geomagnetism and gravimetry)

14) Research on Earth and Oceanic tides.

15) Study of ocean-atmosphere-earth interactions and the perturbations on geodetic observations.

16) Analyze the relationships between bubbles and flicker noise and other ionospheric phenomena (e.g. TIDs).

17) Study of supposed archaeomagnetic jerks during the last 7000 years.

New data acquisition

18) Obtain new archaeomagnetic data in poorly covered regions/time periods (e.g. the Dark Ages, pre-Roman ages, archaeointensidad in western Europe) or periods of particular interest (e.g. 16-17th Century - possible archaeomagnetic jerk).

19) Study the magnetic properties of novel ferromagnetic phases produced during heating of archaeological material (e.g. thermally stable maghaemite, cation-substituted haematite).

20) Obtain new paleomagnetic data from the Betic Cordillera and northern Morocco, in order to complete the pattern of the rotational deformation of these areas.

## **Associated Technical Units**

The Technical Units at Institute of Geosciences, IGEO, more closely related to this Research Sub-line are the following:

### Geodesy, Geophysics and Rock Magnetism

This unit covers instrumentation and observation aspects of those disciplines that define this Research Institute and that complement existing ones across the Earth Sciences in Spain. It refers to Geodetic positioning, gravity, geomagnetism, seismology, paleomagnetism and rock and mineral magnetism.

### Scientific computation and data processing

The general objective of this Technical Unit is to provide advanced resources for scientific computation, as well as for data and image processing. The IGEO will be the only geosciences research center in Spain that has a facility for high performance computing (e.g., massive parallel multi-processor computing). This Unit is divided into three subsections:

- Computation and numerical modelling
- Geophysical and geodetic data processing
- Digital mapping, imaging and GIS

This Technical Unit will have a close connection with the Moncloa Campus of International Excellence (UCM-UPM), in particular with the computer systems purchased in the scientific cluster of Global Change and New Energies.

### External Laboratories: Valle de los Caidos (Madrid) and Lanzarote (Canary Islands)

The two laboratories have a broad national and international reach in aspects of basic and applied research. The areas of interest include the vigilance and study of volcanic and tectonic activity and the development and testing of new instrumentation. This latter activity may lead to strong interaction with the industry of Earth Sciences instrumentation.

The Laboratory of Gravimetry and Earth Tides of the Valle de los Caidos, Madrid, (LGMV) is dedicated to the investigation in the field of the Gravity and Tides. It is located in the Valle de los Caidos, to about 45 km to the northwest of Madrid, in installations assigned by National Patrimony to the CSIC-UCM originally through the former Institute of Astronomy and Geodesy.

The Geodynamics Laboratory of Lanzarote (LGL) is a consequence of agreements with the Cabildo Insular de Lanzarote, the former IAG has scientific facilities in four different places of the island, three of them located at the Volcanic Tunnel of the La Corona Volcano, and the fourth place is inside the National Park of Timanfaya.

For more details about the Technical Units see the corresponding summaries.

## Scientific activity

The scientific activity developed nowadays by the research sub-line has to be described, considering it is a new grouping of separated activities, by means of the activities of the different Research Groups included on it. A clear objective is to solve this, at least partially at the end of the current IGEO Strategic Plan.

### Space Geodesy, Gravimetry and Geomathematics Group

The research carried out for this group, in a non exhaustive way, can be summarized in the following aspects:

a) Mathematical modelling in Earth Sciences: The amount of high precision Earth observation data (geodetic, geophysical and geological) is continually increasing. Prodigious data sets may cover diverse areas and incorporate unconventional techniques, and can be of a quasi-continuous temporal and geographical nature. This requires the need to address the theoretical studies of such data and establish new mathematical models that are capable of maximizing the benefits of the advances made in the technology of data acquisition. New analytical and numerical methods are needed for data processing, modeling and interpretation that take into account the increasing quality, variety, origin, temporal distribution (sporadic or continuous) and spatial distribution (punctual or quasi-continuous). Some recent results in this field are described by Tizzani et al. (2010), van Aalsburg et al. (2010), Camacho et al. (2011a, b, c), Charco and Galán del Sastre (2011), Tiampo et al. (2011), Rodríguez et al. (2012).

b) Space Geodesy, Positioning Systems and Remote Sensing: The applications of artificial satellites for Earth observation are becoming increasingly important. Space Geodesy covers a wide range of applications, from the determination of artificial satellite orbits to the detection of anomalous features (deformation, gravity variations, etc.) that may be associated with geological risks (e.g. volcanic eruptions, earthquakes and ground instability) or global change (variation in water mass, etc.). Research in this area includes various aspects of Earth observation from Space (instrumentation, data treatment techniques, error estimation, combination of terrestrial and space data, combination and interpretation of different space data types, applications, etc.). It represents a major area of Earth Science whose relevance is becoming increasingly important. Some recent results obtained in this line are described by González et al. (2010a), Eff-Darwich et al. (2011) and González and Fernández (2011a, b).

c) Geodetic monitoring of geological and anthropogenic hazards: Geological hazards that produce geodetic effects (e.g. deformation, gravity variations), in particular volcanic eruptions, earthquakes and ground instability, threaten a large part of the global population and may produce significant annual financial costs. Nor can anthropogenic hazards - those caused by human activity within the natural and urban environment - be neglected. Geodetic techniques provide valuable tools for the monitoring of both kinds of hazards, therefore they will represent one of the principal research areas in the next few years

Within this area two fundamental aspects can be recognised: the observation of geodetic effects and the interpretation of the anomalies observed, using theoretical models and inversion techniques. Therefore it is necessary to develop methodologies for the interpretation of geodetic observations that may be used by the institutions responsible for decision making in crisis situations - methodologies that should be tested, validated and above all rapidly and easily executable. Some recent results are described by González et al. (2010a, b), D'Oreye et al. (2011), González and Fernández (2011a, b), and Samsonov et al. (2011).

#### Palaeomagnetism, Rock Magnetism and Geomagnetic Modelling Group

The Earth's magnetic field is principally of internal origin. The composition of the outer core coupled with its complex dynamic behaviour gives rise to a magnetic field that has played an important role in the evolution of the planet and of life itself. Understanding the behaviour of the magnetic field over geological timescales is a principle goal of palaeomagnetism. Along with this, palaeomagnetism has important applications in other areas of geoscience and archaeology, marking it as a profoundly multidisciplinary subject involving physicists, geologists, geophysicists, mathematicians and archaeologists.

The Palaeomagnetism, Rock Magnetism and Geomagnetic Modelling Group is currently involved in the following key areas: plate tectonics and palaeoreconstructions (dynamics of the Iberian plate and the Iberia-Africa plate margins), geomagnetic field reversals and excursions, magnetic properties of the K-T boundary, meteorite magnetic properties, archaeomagnetism and archaeomagnetic dating, palaeosecular variation in Iberia and North Africa, environmental magnetism and palaeoclimate, magnetic properties of rocks, sediments and single crystals and modelling of the recent (last 8000 years) geomagnetic field modelling over the last 8000 years.

Archaeomagnetism has been a major field of interest of the group since 1996. Over the past 15 years the group has obtained more than 100 new data for the Iberian Peninsula, leading to the publication of the first reference secular variation curve for the region, covering the last 2000 years. This has led to a better understanding of the geomagnetic field and its variations on a trans-European scale and to the development of archaeomagnetic dating as a viable tool for Spain, Portugal and northern Africa.

The data have been a key element in developing geomagnetic field models, as set out below. Current and future objectives of the group are to extend the data set back in time and to fill in gaps in the temporal record (e.g. the Dark Ages between the 5<sup>th</sup> and 9<sup>th</sup> centuries AD), improve the geographical distribution of the data (e.g. to include northern Iberia and northern Africa, Gomez-Paccard et al, accepted) and to recover the full geomagnetic field vector information (both direction and intensity) of the Earth's recent past.

The Palaeomagnetism Research Group has also proposed the first regional models of the geomagnetic field in the European region based on palaeomagnetic data (archaeomagnetic data and lake sediment records). These regional models (Pavón-Carrasco et al 2009, 2010) allow the determination of the palaeosecular variation of the geomagnetic field for the last 8000 years: from 6000 BC to 1900



AD, connecting with the instrumental models, such as the IGRF models. Several strategies have been developed for the inversion process of the palaeomagnetic data by applying, in space, the spherical cap harmonic analysis SCHA and its revised version R-SCHA2D. In time, all models were obtained using the sliding overlapping windows method. Both models, called SCHA.DIF.3K (Pavón-Carrasco et al 2009) and .8K (Pavón-Carrasco et al 2010), can be used for analysing the palaeosecular variation of the geomagnetic field in Europe for the last 8000 years and related phenomena, such as archaeomagnetic jerks, the possible (or causal) relationship between the Earth's magnetic field and climate change, or the Geocentric Axial Dipole hypothesis (GAD). Moreover, it has been shown how they can be used as a tool for archaeological dating (Pavón-Carrasco et al 2011).

The Palaeomagnetism Research Group has also an intensive record in the sub-field of rock magnetism. In this line, the group has focussed on i) the identification of magnetic carriers in common palaeomagnetic and archaeomagnetic materials and exotic materials such as meteorites and meteor impact rocks, ii) fundamental rock magnetic properties in natural crystals and iii) anisotropy of magnetic fabrics in natural crystals and rocks.

Among the most important achievements in the identification of magnetic minerals of palaeomagnetic interest, the group has studied the characteristics of magnetic minerals carrying remagnetised directions and the magnetic fingerprint of remagnetisations. In the field of archaeomagnetism, the group has identified new magnetic phases with unique characteristics previously unrecognised in archaeomagnetic samples (McIntosh et al 2011). In the field of natural crystals, the group has published single crystal properties in some common rock forming minerals like phyllosilicates or magnetic minerals like goethite (Martin-Hernandez and Garcia Hernandez 2010) and hematite (Guerrero-Suárez and Martin-Hernandez 2011). It has also applied new mathematical models for the separation of magnetic sub-fabrics and determined the anisotropy constant in antiferromagnetic phases of palaeomagnetic interest (Martin-Hernandez and Guerrero-Suárez 2011).

In addition to this, new detailed Jurassic palaeoreconstructions of the Iberia-Eurasia-African plates have been recently proposed by the group (Osete et al 2011), along with new palaeopoles for the African tectonic plate (Palencia-Ortas et al 2011) as well as magnetostratigraphy (Comas-Rengifo et al 2010a, 2010b) and studies on the internal deformation of the Iberia-Africa plate boundary and central Mexico (Ruiz-Martinez et al 2010).

#### Terrestrial and Planetary Magnetic Field and Aeronomy Group

The research of this group fundamentally focuses on the study of the ionospheres of the Earth and Mars and on the modeling of the movement of charged particles in the Mars surface.

In the study of Earth's ionosphere special attention is being paid to the analysis of the equatorial plasma depletions known as Equatorial Plasma Bubbles and to the effects the ionosphere produces both on the electromagnetic waves transmission (scintillation) and on the Precise Point Positioning.

Following previous researches (Portillo et al 2008), a new post-processing technique has been developed to detect and characterize ionospheric plasma bubbles from GPS derived sTEC (slant Total Electron Content) data. A Java Program has been developed to implement this technique allowing its use in all the operative systems (OS) and the internet (Magdaleno et al 2011a). This method has been applied to data from the International GNSS Service (IGS) stations located in the American, Asian and African equatorial sectors. For years of high solar activity it was found that the number of depletions with amplitudes higher than 10 TECu is consistent with the results obtained by other authors for the topside ionosphere using satellite data. Our study draws the same conclusions but analyzing GPS derived sTEC data instead of in situ measurements (Magdaleno et al 2011b). A detailed analysis of the EPBs occurrence in South America has been also accomplished (Magdaleno et al 2011c).

Concerning the effect of the ionospheric disturbances on precise point positioning, a recent study (Moreno et al 2010) has proved that at equatorial latitudes post-sunset large changes in the Rate of Total Electron Content (ROT) can adversely affect the GPS signal, degrading accuracy and reliability of positioning. The estimated altitudes can contain very significant errors for a single-epoch position determination.

In the case of the Martian ionosphere, empirical models are being developed using radio-occultation data from the Mars Global Surveyor and ionospheric soundings obtained by the MARSIS instrument on board the Mars Express. The first step in this line of study was to apply the Chapman-layer model to a significant sample of radio-occultation data and verify the degree of validity in order to adjust the electron density profiles. The situation of the ionosphere was analyzed under different conditions of latitude, longitude, time of observation, season of the Martian year and solar activity, and these were compared with the characteristics and variations in the Earth's ionosphere (Sánchez-Cano et al 2010). Successive improvements of this initial model have been developed by using ionospheric soundings and considering solar activity, zenith angle, solar distance and annual station influences.

On the other hand, continuing with studies on Mars, numerical models have been proposed to analyze the behavior of the magnetized and charged particles near the surface of Mars. In this way, first we have worked with a theoretical magnetic field, and we have studied the trajectories described by charged particles (electron and proton) moving in this magnetic field. Then we have done the same calculations for other theoretical magnetic fields. The goal of this work is to analyze the behavior of the particles that come from the solar wind when they interact with the magnetic field on Mars. Also we want to link these phenomena with the presence of auroras on Mars, and use the real data from the Mars Global Surveyor to improve our models.

Likewise, studies to localize and characterize North Polar structures between Olimpia Undae and Scandia Cavi, an area previously poorly understood, are being carried out. All the Martian research takes place in the frame of the Meiga-METNET projects and with the collaboration of the European Space Agency.

### Gravimetry, Tides and Geodynamics Group

The activity of this group concerns several geodetic and gravimetric topics. On the one hand, the studies of Earth tides and ocean tide loading. The Earth tide models obtained are used to correct precise geodetic and gravimetric measurements and to develop an observation network along the Iberian Peninsula, Canary Islands and North of Africa. Most recent stations have been established in Algodonales (Cádiz), El Hierro and Melilla. Harmonic analysis through the method of least squares is applied to estimate the observed tidal signal, and regression models are included to identify atmospheric perturbations (eg VAV program). Time series of gravity, tilt and strain measurements available in these researches are applied to investigate deformations of the Earth's crust. However, the main disturbing effect involved in these measures is the ocean. Therefore, ocean models based on tide gauge and satellite altimeter data assimilated into a hydrodynamic model are developed to compute the ocean tide loading (Benavent et al. 2009). In turn, this research has led to study the elastic response of Earth's crust, on tidal time scales (Arnosó et al 2011).

On the other hand, the research on Gravimetry is focused on the development of density contrasts models obtained by gravity inversion, with applications in volcanic islands and in archaeology. The mathematical methodology developed by this group, based on the application of genetic algorithm, provides 3D analysis of subsurface geological structures. Structural models for the islands of Fuerteventura, La Gomera and El Hierro in the Canaries and for some of the islands of Azores and Cape Verde archipelagos have been obtained most recently (eg, Montesinos et al 2006). Presently, joint inversion of gravity, magnetic and microseismic data are under development. The Geodynamics Laboratory of Lanzarote, which is a priority research objective of this group, makes it possible to develop instruments and methods for permanent geodetic and geophysical observations applied to studies in volcanic areas. Other researchers are related to the application of gravity observing methods, paying special interest to calibration and instrumental sensitivity. In addition, the gravity laboratories located in Madrid and Valle de los Caídos allow to develop these activities.

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